PROJECT AUTHORIZATION NO. HWY-2005-10

under

MASTER AGREEMENT FOR RESEARCH AND TRAINING SERVICES BETWEEN THE NORTH CAROLINA DEPARTMENT OF TRANSPORTATION AND NORTH CAROLINA STATE UNIVERSITY ON BEHALF OF THE INSTITUTE FOR TRANSPORTATION RESEARCH AND EDUCATION
(Contract No. 98-1783)

Project Title: Traffic Control Design for Portable Concrete Barriers

Formal Statement of Work: See attached proposal

Period of Performance: July 1, 2004 – June 30, 2005

Budget Authorization: $87,168 (one year)

Property to be Furnished by the Department: None

Key Personnel: Amir Mirmiran, Shamim Rahman

Project Monitor: Shannon Lasater________________________

Additional Terms and Conditions: Research Project Guidelines as posted on ITRE's website at *http://itre.ncsu.edu/research/ongoingguidelines.htm.*

IN WITNESS WHEREOF, the parties hereto have executed this Project Authorization as of

_________________________, 2003.

NORTH CAROLINA STATE UNIVERSITY

BY:________________________________
Principal Investigator

BY:________________________________
N. C. State University

BY:________________________________
Director of ITRE

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

BY:____________________________

FY 2005
NCDOT

Research Proposal

Subcommittee:	Operations
Project Title:	Traffic Control Design for Portable Concrete Barriers
Submittal Date:	April 16, 2004
Organization:	North Carolina State University

Researchers:

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EXECUTIVE SUMMARY

This proposal is developed in response to *Research Idea OP-06* in the NCDOT FY-2004 *Call for New Research Ideas,* proposed by Mr. J. Stuart Bourne and Mr. Joseph Ishak of the NCDOT Traffic Control, Marking and Delineation. The proposal also adheres to the review comments received from the *Operations Research Subcommittee* on the pre-proposal, and following telephone discussions with Mr. Bourne on the subject.

The purpose of traffic barriers is to protect the traveling public as well as to provide a safe work zone for the construction crew on the side of the road. Design of the safe back distance has several implications. On the one hand, there is the issue of safety of the construction workers and the public. On the other hand, there is the issue of practicality and economic viability of highway construction projects.

The North Carolina Department of Transportation (NCDOT) is currently in the process of developing its own traffic control design manual. The existing section on temporary traffic barriers requires calculating deflection of free standing barriers using an impact severity formula based on the Kinetic Energy principle. The design method, although approximate, is neither simple nor user friendly. Moreover, its applicability to the NCDOT and the Oregon Type F barriers, which the NCDOT plans to use, is very much questionable. The objective of this research is to develop design aids, i.e., design charts and tables, for portable concrete barriers based on calibrated numerical analysis and rational design approach to be included in the new NCDOT traffic control design manual. <u>Since both the NCDOT and the Oregon Type F barriers have been recently crash tested, only numerical analysis (and no crash test) is required for the design of both types of barriers.</u>

Once the physical impact problem is modeled and calibrated against the recent crash tests on both the NCDOT traffic barriers and the Oregon Type F traffic barriers, it can be used to determine the safe back distance as well as the length of need for free standing portable concrete barriers under different design conditions, including barrier type, design speed, vehicle mass, lane configuration, and roadway geometry, i.e., tangent or curved segments with different radii of curvature. The deliverable of the project is design aids for the NCDOT barriers and the Oregon Type F barriers for use in the NCDOT traffic control design manual. Benefits to the NCDOT may be realized as safety, cost-savings, and design efficiency on all roadway construction projects.

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RESEARCH PLAN

Introduction

This proposal is developed in response to *Research Idea OP-06* in the NCDOT FY-2005 *Call for New Research Ideas.* The research idea was proposed by Mr. J. Stuart Bourne and Mr. Joseph Ishak of the NCDOT Traffic Control, Marking and Delineation. The PIs submitted their pre-proposal on October 10, 2003. The Operations Research Subcommittee recommended the development of a full proposal, as stated in the November 25, 2003 letter of Mr. Rochelle, State Research Engineer. In the letter, the Subcommittee has recognized that a preliminary model for impact kinetic energy and associated deflections already exists, as developed by the PIs in Summer 2003. As such, the Subcommittee has asked that the proposal be streamlined to contain only that which is necessary and that the budget will also reflect the streamlined proposal. The PIs have accordingly developed this proposal.

Problem Statement

The NCDOT is in the process of developing its own traffic control design manual. The existing section on temporary traffic barriers requires calculating deflection of free standing portable concrete barriers (PCB) using an impact severity formula based on the Kinetic Energy principle, as follows:

$$IS = \tfrac{1}{2} M \left(VSin\theta\right)^2$$

where *IS* is the impact severity in kilo Jules, *M* is the vehicle mass in kilograms, *V* is the vehicle speed in meters per second, and θ is the impact angle in degrees. The method calls for safe back distances of 1 foot to 6 feet depending on the impact severity, varying between 10 and 100 kilo Jules. The impact severity is determined from an existing table. The design method, although approximate, is neither simple nor user friendly. Moreover, its applicability to the NCDOT and the Oregon Type F barriers, which the NCDOT plans to use, is very much questionable.

Recent crash tests have shown the need for greater safe back distances of up to 9 feet for the NCDOT barriers. The safe back distance is a costly measure in construction projects, especially if more right of way, temporary pavement, detour, or more phases of traffic control sequence is required. The barriers are often placed in a narrow space along the construction area, parallel to the edge of retaining walls, or along a bridge deck under staged construction. The limited area behind the barrier should allow for its deflection under the impact of an errant vehicle. Optimum design of the space behind the barrier is therefore of great importance. On the one hand, there is the issue of safety of the construction workers and the public. On the other hand, there is the issue of practicality and economic viability of highway construction projects in the State of North Carolina.

Regarding the safety issue, it suffices to note that highway construction is among the most hazardous construction activities, with 39 deaths per 100,000 U.S. workers, as compared to only 6 deaths per 100,000 U.S. workers in all other industries (*U.S. Bureau of Labor Statistics*). Of this number, the highest fatality rate, which is approximately 23%, is due to workers being struck by vehicles intruding the work zones. In order to achieve a uniform level of safety, the National Cooperative Highway Research Program (NCHRP) has developed a comprehensive set of standards and procedures for evaluating the performance of permanent and temporary highway safety features in *Report 350*, "Recommended

Procedures for the Safety Performance Evaluation of Highway Features" (Ross et al. 1993). Figure 1 shows an article from the July 2003 issue of the Roads & Bridges, which highlights the work zone safety and shows a crash impact on temporary barrier walls.

Comparison of the recent crash tests on NCDOT barriers and the current design procedures in the traffic control design manual highlights the urgent need for updating the design manual based on rational design guidelines. Moreover, the NCDOT plans to use Oregon Type F barriers in its construction projects. The guidelines need to be accompanied by simplified and user-friendly design aids (charts and tables) for safe back distance and length of need. Design charts, therefore, should be based on actual design parameters such as barrier type, design speed, vehicle mass, lane configuration, and roadway geometry, i.e., tangent or curved segments with different radii of curvature. The updating of the traffic control design manual will help provide for a cost-efficient, yet safe design. Since both the NCDOT and the Oregon Type F barriers have been recently crash tested, only numerical analysis (and no crash test) is required for the design of both types of barriers.

Research Objectives

The objective of this research is to develop design aids, i.e., design charts and tables, for portable concrete barriers (PCB) based on calibrated numerical analysis and rational design approach to be included in the new NCDOT traffic control design manual. Once the physical impact problem is modeled and calibrated against the recent crash tests on both the NCDOT traffic barriers and the Oregon Type F traffic barriers, it can be used to determine the safe back distance as well as the length of need for free standing portable concrete barriers under different design conditions, including barrier type, design speed, vehicle mass, lane configuration, and roadway geometry, i.e., tangent or curved segments with different radii of curvature.

Literature Review

Precast Concrete Barrier (PCB) is a frequently used feature for work zone traffic control. Different states used varying designs of these PCBs. These barriers are expected to safely withstand severe vehicle impact conditions. In order to achieve a uniform level of safety, the National Cooperative Highway Research Program (NCHRP) has developed a comprehensive set of standards and procedures for evaluating the performance of permanent and temporary highway safety features in Report 350, "Recommended Procedures for the Safety Performance Evaluation of Highway Features" (Ross, et al. 1993). The FHWA has required that by no later than October 2002, states must confirm that their safety features are acceptable under these new standards.

The NCDOT has been using several types of barrier. Recently on the basis of a crash test, a specific barrier was accepted by the FHWA. The accepted barrier is a standard 32 in high New Jersey shape portable barrier in segment lengths of 10 ft. The base width is 24 in and the barrier tapers to a 6 in top width. The barrier sections are held together with some sort of assembly, varying in design. A typical set of barriers is shown below in Figure 2. There exist some concerns about the currently adopted 'back distance' between the barriers and an edge or another working zone. Of course this distance should be governed by a realistic estimate of the maximum displacement of the barrier under an anticipated vehicle impact.

WORK-ZONE SAFETY

Shortening time, not lives

SCDOT attacks accelerated construction project with heightened safety measures

David Henderson, P.E.
Contributing Author

Imagine refinishing all of the hardwood floors in your house, while still living in it. That's very similar to what we are doing during the reconstruction of I-385."

This statement is frequently made by Area Manager Randy Green as he addresses community groups interested in their project. Green is a member of the South Carolina DOT Construction Resource Managers (CRM-West) team, responsible for providing information to the media and community about the department's accelerated projects in upstate South Carolina.

I-385 is currently one of the largest components of a program of accelerated highway improvements, which SCDOT refers to as the "27 in 7 Program." This program will provide in just seven years what would normally take 27 years to plan and construct through traditional means.

The I-385 Improvements Project is widening 5.8 miles of interstate between I-85 and downtown Greenville, S.C. Serving an urban corridor, including nearby major corporations such as Michelin Tire and BMW, I-385 averages more than 60,000 vehicles per day. Engineers are expecting a 50% increase to over 92,000 by 2020. By adding more lanes and upgrading the interchanges,

A crash impact on the temporary barrier wall shows just how close four workers were to catastrophe on I-385. The driver who lost control of her truck in this crash exceeded the posted speed limit and was apparently distracted.

WWW.ROADSBRIDGES.COM

Figure 1. Crash Impact and Its Effect on Work Zone Safety (Roads and Bridges 2003)

Figure 2. A Typical Precast Concrete Barrier Assemblage (MacDonald and Kirk, 2001)

These barriers need to be designed such that they can withstand severe impacts from vehicles. A typical crash situation is depicted below in Figure 3.

Figure 3. A Typical Crash Showing Angle of Impact (MacDonald and Kirk, 2001)

A typical post-crash response of the barriers is shown below in Figure 4. A safe design of barrier requires mainly the following conditions:

1. No structural failure of the concrete barrier
2. No excessive displacement of the barrier
3. Occupant impact velocity, and ride-down acceleration.

Considering the situation of a typical barrier assembly resting directly on the surface of a pavement, we can represent the essential features of the problem in Figure 5.

Figure 4 Deflected Shape of the Barrier after Crash (MacDonald and Kirk, 2001)

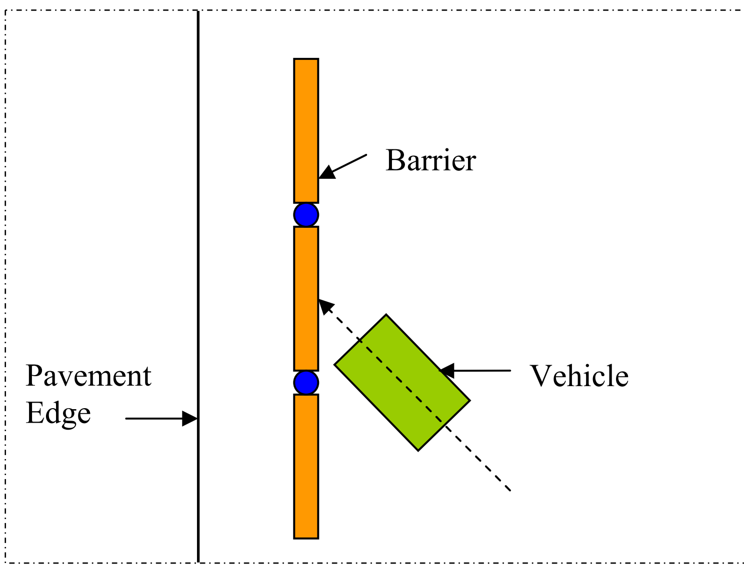


Figure 5. Essential Features of the Barrier Problem

In terms of underlying mechanics, the problem at hand involves a collision between two deformable bodies: the vehicle and the barrier system. In their initial conditions, the barrier system is at rest while the vehicle is moving at certain velocity. In addition to the forces of impact, the barrier system is subjected to additional forces such as friction between the barrier and the pavement. The evaluation of the post-impact response of both the barrier and the vehicle is needed to ensure a safe design. In relation to the design of the barrier system, one important consideration is its displacement due to vehicular impact.

The NCHRP 350 (Guidelines for the Crash Tests and the Required Performance Criteria) sets the basic requirements for crash tests. Depending on the feature being evaluated, there are up to six test levels that can be selected. In general, the lower test levels are applicable for evaluating features to be used on lower service level roadways and certain types of work zones while the higher test levels are applicable for evaluating features to be used on higher service level roadways or at locations that demand a special, high performance safety feature (Ross, et al. 1993). A temporary barrier would not normally be designed for impact conditions greater than test level 3, except under very unusual conditions. It should perform acceptably using the 820C and 2000P type vehicles with all appropriate tests. The evaluation criteria for this test are as follows (Ross, et al. 1993):

> "*A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride or over-ride the installation, although controlled lateral deflection of the test article is acceptable.*
>
> *D. Detached elements, fragments or other debris from the test article should not penetrate of show potential for penetration the occupant compartment, or present an undue hazard to other traffic, pedestrians of personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*
>
> *F. The vehicle should remain upright during and after collision, although moderate roll, pitching and yawing are acceptable.*
>
> *K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*
>
> *L. The occupant impact velocity in the longitudinal direction should not exceed 12m/sec, and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 Gs.*
>
> *M. The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with test device.*"

In addition to these criteria, when PCB is used in work zones to separate traffic in high-occupancy vehicle (HOV) lanes, special attention should be paid to the lateral deflection it may undergo during a vehicular impact. Because the amount a given installation can deflect without adverse consequences depends on site conditions, it is not feasible to establish limiting deflection values for crash tests of these barriers. Rather, it is important to accurately measure and report barrier displacement that occurs during the test so that a user agency can make an objective assessment of the appropriateness of the barrier for its intended application.

Some crash tests have been performed on various PCBs made by various manufactures. Summary and comparison about the test results are listed in Table 1-3. For the purpose of this review here, the PCBs are divided into three categories according to their shape: NJ-shape (Jersey barriers), F-shape, and other shape.

For NJ-shape barriers, Idaho Transportation Department concrete barrier has minimum Maximum Deflection of about 3 ft during the NCHRP 350 test 3-11. For F-shape barriers, Oregon DOT standard F shape precast concrete barrier has the least Maximum Deflection of 2½ ft during the NCHRP350 test 3-11. In general, barrier deflection can be minimized by using longer and heavier barrier segments and by using joints that can develop a bending moment of 50 kip-ft or higher.

Several methods for improving the performance of PCBs are reported in McDevitt (2000). They include the following:

- *"Pulling the barrier segments tight and anchoring the end segments to the ground are also very helpful in reducing the lateral deflections."*
- *"Anchoring each barrier segment with steel pin driven into the ground is very effective, but it makes the barrier less portable and labor-intensive. Pin and loop connections are widely used to connect adjacent segments because they can readily accommodate horizontal curvature and changes in vertical grade. However, only after the joint has undergone a significant amount of rotation, the pin and loop connections can develop bending-moment capacity."*
- *"Loops made of reinforcing bars are better than wire loops because they can resist torsion rotations of the barriers at the joints. A washer or cotter pin at the bottom end of the steel pin is necessary to prevent the pin form jumping vertically out of the loops upon impact."*

Table 1. Crash Test Information for New Jersey (NJ) Shape PCB

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
Idaho DOT (2)	NCHRP 350 Test 3-11	E-TECH Testing services, Inc.	**Type**: Idaho Transportation Department 6095 mm concrete barrier. **Shape**: standard New Jersey profile. **Height**: 810 mm (32 inches) **Length**: 6095 mm (20 feet) **Base Width**: 610 mm (24 inches) **Top Width**: 150 mm (6 inches). **Segment Weight**: 3630kg (8000 lbs) **Installation Length**: 73.2m (overall installation)	Adjacent segments were connected using 31.8 mm (1.25 inch) diameter steel pins passed through four loops made from 19-mm (0.75-inch) diameter steel bars. Longitudinal reinforcement consisted primarily of six #16 bars per segment.	Model: 1995 Chevrolet C25OO 3/4 Ton Pickup Mass: 1994kg	**Speed**: 101.1 km/h for bolted connection, 99km/h for pinned connection. **Angle**: 25 for both connections. **Impact Severity**: 138.9 kJ for bolted connection, 134.6kJ for pinned connection. **Maximum occupant impact velocity**: 5.9m/sec **Maximum ridedown acceleration**: 11.7 g's **Roll angle**: 52.7 degrees	1.0 m for bolted connection, 1.1 m for pinned connection.
Ohio DOT (3)	NCHRP 350 Test 3-11	Transpor-tation Research Center	**Type**: Ohio Department of Transportation's 3-m long New Jersey profile temporary concrete barrier. **Shape**: standard New Jersey profile **Height**: 810-mm (32-in). **Length**: 3.0m (10 feet). **Base Width**: 610-mm (24-in) **Top Width**: 150-mm (6-in). **Installation Length**: 76m (244 ft) including ten 3-m (10-ft) sections in the impact area, three 3.8 m (12.5-ft) sections upstream of the impact area, and nine 3.8-m (12.5-ft) sections at the trailing end of the test installation.	The pin and loop connection between segments is comprised of round 19-mm (1.25-in) diameter steel bars bent to an inside radius of 44 mm (1.7in). A galvanized 32-mm (1.25-in) diameter high-strength bolt, 560-mm (22-in) long, with heavy plate washers and a bottom hex nut, connects adjoining segments. Reinforcing consists of five longitudinal 16M (#5) bars with four 10M (#3) stirrups at each end on 150-mm (6-in) centers, with three additional stirrups evenly spaced from the end stirrups on 483-mm (19-in) centers.	Ford F-250 pickup truck	**Maximum occupant impact velocity**: 6.0m/sec (20ft/sec) **Maximum ridedown acceleration**: 7.2g's **Roll angle**: 46 degrees.	1.67m (5.5ft)

Table 1. Crash Test Information for New Jersey Shape PCB (Continued)

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
New York DOT (4)	NCHRP 350 Test 3-11	Texas Transpor-tation Institute	**Type**: New York DOT Portable Concrete Barrier with I-Beam Connection **Shape**: standard New Jersey profile. **Height**: 810 mm (32 inches) **Length**: 6.1m **Base Width**: 610 mm (24 inches) **Top Width**: 150 mm (6 inches). **Installation Length**: 61.0 m (10 barrier segments)	Adjacent barrier segments are connected with steel "I" shaped pins which fit inside steel tubes cast into each end of the barrier segments. These tubes are 513-mm long and made form ASTM A500 Grade B or C steel. In cross section, they are 102 mm*102mm * 13 mm, with a 25-mm vertical slot cut into the exposed face of the tube at the end of each barrier segment. Reinforcing consists primarily of four longitudinal 16M bars with three 13M stirrups located at each end of the barrier.		**Maximum occupant impact velocity**: 5.6m/sec **Maximum ridedown acceleration**: 8.9 g's **Roll angle**: 19 degrees	1.27m
Georgia DOT (5)	NCHRP 350 Test 3-11	Texas Transpor-tation Institute	**Type:** Georgia temporary concrete barrier. **Shape**: New Jersey profile **Height**: 810-mm (32-in). **Length**: 3.0m (10 feet). **Base Width**: 760-mm **Top Width**: 300-mm. **Installation Length**:55.3 m total installation length with 18 barrier segments.	The connection between segments consists of a 638-mm long, 32-mm diameter A-307 steel double hex bolt inserted through 4 loops (2 at each end of each barrier segment) made form number 16 steel bars and retained with a hex nut at its lower end. Reinforcing consists primarily of six longitudinal number 13 bars with three bars located on each face of the barrier. Eleven V-shaped number 13 bars (4 at each end on 200-mm centers and 3 evenly spaced between the ends) are used in each segment.	Model: 1996 Chevrolet 2500 pickup truck. Mass: 2000Kg	**Speed**: 99.9km/h **Angle**: 25.6 degrees. **Maximum occupant impact velocity**: 6.5m/sec **Maximum ridedown acceleration**: 4.9g's **Roll angle**: 38 degrees.	1.93 m

Table 1. Crash Test Information for New Jersey Shape PCB (Continued)

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
NC DOT (6)	NCHRP 350 Test 3-11	Transpor-tation Research Center	**Type**: North Carolina Department of Transportation 3-m long New Jersey profile temporary concrete barrier. **Shape**: standard New Jersey profile. **Height**: 810 mm (32 inches) **Length**: 3m (10 feet) **Base Width**: 610 mm (24 inches) **Top Width**: 150 mm (6 inches). **Installation Length**: 60m (200ft) with 20 barrier segments	The loop connection between segments is comprised of round 19-mm (0.75-in) diameter steel bars bent to an inside radius of 51 mm (2.0in). There are two such loops at the top of each segment on one end and s single loop on the opposite end. The bottom loops are reversed, with a single bottom loop on the end with a double top loop and a double bottom loop on the opposite end. Barrier segments are connected by positioning the single loops between the double loops at each end and inserting a galvanized 32-mm diameter high-strength bolt, 660-mm long through the all six loops. Reinforcing consists of two longitudinal 13M (#4) bars in the barrier stem and a u-shape section of 6*6*w2.9 welded wire fabric throughout the barrier length.	Ford F-250 pickup truck	**Speed**: 100.4 km/h (62.4mph) **Angle**: 25 degrees **Maximum occupant impact velocity**: 5.1m/sec (16.7ft/sec) **Maximum ridedown acceleration**: 7.7 g's **Roll angle**: 48 degrees	1.54m (5.0ft)
EASI-SET Industries (7)	NCHRP 350 Test 3-11	Texas Transpor-tation Institute	**Type**: J-J Hooks Jersey Shape Portable Concrete Barrier **Shape**: standard height (813mm) New Jersey profile **Height**: 813-mm. **Length**: 3658-mm **Base Width**: 600-mm **Top Width**: 230-mm **Installation Length**: 58.56m with 16 segments	The hooks were formed from 10-mm thick steel plates which were connected through the barrier by three No.16 ASTM A706 Grade 60 reinforcing bars. Additional reinforcement in the barrier consisted of welded wire fabric throughout its length.	1993 Chevrolet 2500 pickup truck. Mass: 2000kg	**Speed**: 101.0km/h **Angle**: 25 degrees **Maximum occupant impact velocity**: 5.9m/sec **Maximum ridedown acceleration**: 5.7 g's **Roll angle**: 25 degrees	1.3m

Table 2. Crash Test Information for F-Shape PCB

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
Virginia DOT (8)	NCHRP 350 Test 3-11	Texas Transportation Institute	**Type**: Virginia DOT portable concrete barrier **Shape**: F shape. **Height**: 810 mm (32 inches) **Length**: 6100- mm **Base Width**: not known **Top Width**: not known **Installation Length**: 43.3m overall installation including five 6100-mm segments with two 3100-mm long segments added at each end of the test installation.	Adjacent segments are connected by 25-mm diameter ASTM A36 steel pins 610-mm long which pass through loops fabricated with 20-mm diameter steel bars. Each segment was made from 30 Mpa concrete and contains three longitudinal #19 bars and one longitudinal #13 bar.	Model: 1994 Chevrolet 2500 Pickup truck Mass: 2000kg	**Speed**: 100.6 km/h **Angle**: 24.6 degrees **Maximum occupant impact velocity**: 5.9m/sec **Maximum ridedown acceleration**: 12.4 g's **Roll angle**: 12 degrees	1.83m
Pennsylvania DOT (9)	NCHRP 350 Test 3-11	Texas Transportation Institute	**Type**: PennDOT Portable Concrete Barrier. **Shape**: modified F shape **Height**: 860-mm **Length**: 3.6m **Base Width**: 610-mm (24-in) **Top Width**: 230-mm. **Installation Length**: 58.6m with sixteen barrier segments used.	The connection between segments is a 300-mm long * 690-mm high * 13-mm thick steel plate that fits loosely into a vertical slot formed into the end of each segment. The first and last segments are both anchored with eight number 19 rebars driven into the pavement. Reinforcing consists of three longitudinal number 13 bars with five number 13 stirrups at each end on 50-mm centers.	Model: 1996 Chevrolet 2500 Pickup truck Mass: 2000kg	**Speed**: 100 km/h **Angle**: 24.2 degrees **Maximum occupant impact velocity**: 6.3m/sec **Maximum ridedown acceleration**: 9.5g's **Roll angle**: 19 degrees.	2.555m
Indiana DOT (10)	NCFRP 350 Test 3-11	Transportation Research Center in East Liberty, Ohio	**Type**: Indiana DOT temporary concrete barrier. **Shape**: F shape **Height**: 790-mm **Length**: 3.0m **Base Width**: 600-mm **Top Width**: 250-mm **Installation Length**: 79m including twenty six barrier segments.	Adjacent segments were connected with a 30-mm diameter hex head bolt 660-mm long with a hex nut at the bottom. Two tubular spacers were used, a 250-mm long TS 100*50*8 under the bolt head, and a 400-mm long TS 100*50*8 above the nut. These spacers were intended to fill the gap between barrier segments to limit deflection. Reinforcing consisted of four 19M bars which also formed the loops at the ends of each segment.	2000-kg pickup truck	**Speed**: 102.9 km/h **Angle**: 23.8 degrees **Maximum occupant impact velocity**: 6.1m/sec **Maximum ridedown acceleration**: 10.4g's **Roll angle**: <5 degrees.	1.6m

Table 2. Crash Test Information for F-Shape PCB (Continued)

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
Oregon DOT (11)	NCHRP 350 Test 3-11	Karco Engin-eering Automo-tive Research Center	**Type**: Oregon DOT standard F shape precast concrete barrier **Shape**: standard F shape. **Height**: 810 mm (32 inches) **Length**: 3.81m (12.5 feet) **Base Width**: 610-mm **Top Width**: 240-mm. **Installation Length**: 61m with sixteen barrier segments	The pin and loop connection consisted of two 19-mm A36 steel loops near the top of one segment end, above a single 19-mm steel loop near the bottom on the same end. The corresponding loops on the adjacent barrier segment consisted of a single loop near the top and double loops on the bottom. When placed together, the single loops fit between the double loops, forming two connection points, each consisting of three loops.	Model: 1995 Chevrolet C25OO 3/4 Ton Pickup Mass: 2041kg	**Speed**: 100.74 km/h (62.6 mph) **Angle**: 25 degrees **Maximum occupant impact velocity**: 5.8m/sec **Maximum ridedown acceleration**: 18.2 g's **Roll angle**: 15 degrees	30 in.
Oregon DOT (11)	NCHRP 350 Test 3-11	Karco Engin-eering Automo-tive Research Center	**Type**: Oregon DOT tall F shape precast concrete barrier **Shape**: tall F shape **Height**: 1065-mm **Length**: 3.02m . **Base Width**: 660-mm. **Top Width**: 230-mm. **Installation Length**: 60.96 m with twenty segments	The connection between segments consisted of two sets of two perforated C-shape steel channels with the open sides alternately positioned such that one leg of each channel fits between the legs of the mating channel on the adjacent barrier segment. A 25-mm diameter ASTM A449 end bolt, 760-mm long, was inserted through holes in each C-channel leg and into a nut welded to the bottom of the lower C-channel, effectively forming eight points of connection.	Model: 1995 Chevrolet Pickup Truck Mass: 2024kg	**Speed**: 102.38 km/h (63.62 mph) **Angle**: 25 degrees **Maximum occupant impact velocity**: 6.22 m/sec **Maximum ridedown acceleration**: 19.36 g's **Roll angle**: 16.04 degrees.	32 in.
Oregon DOT (12)	NCHRP 350 Test 4-12	Karco Engin-eering Automo-tive Research Center	Same as above	Same as above	Model: 1995 Ford F-600 Box Truck Mass: 7917kg	**Speed**: 76.06 km/h (47.27 mph) **Angle**: 15 degrees **Maximum occupant impact velocity**: 2.74 m/sec **Maximum ridedown acceleration**: 6.78 g's **Roll angle**: 9.5 degrees	32.5in.

Table 2. Crash Test Information for F-Shape PCB (Continued)

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
University of Nebraska-Lincoln (13)	NCHRP 350 Test 3-11	Midwest Roadside Safety Facility	**Type**: F-shape Temporary Concrete Median Barrier **Shape**: F shape. **Height**: 810-mm. **Length**: 3800-mm **Base Width**: 570-mm **Top Width**: 200-mm. **Installation Length**: 81.52m	Pin and rebar, pin diameter 31.8 mm, rebar diameter 20-mm	Model: 1986 Chevrolet C20 2WD Mass: 2005kg	**Speed**: 100.3km/h **Angle**: 27.1 degrees **Maximum occupant impact velocity**: <12 m/sec **Maximum ridedown acceleration**: <20 g's	1.14m

Table 3. Crash Test Information for other type PCB

Manufacture	Test Level	Test Agency	Test Article	Connection	Test Vehicle	Impact Conditions & Occupant risk values	Maximum Deflection
Barrier Systems, Inc. (14)	NCHRP 350 Test 3-11	Safe, Technol-ogies, Inc.	**Type**: Quickchange Moveable Barrier **Height**: 813mm **Length**: 1000mm **Base Width**: 810 mm **Top Width**: not known. **Segment weight**: 650kg **Installation Length**: 75m overall (75 QVB sections)	Adjacent segments are pinned together with a 28.6-mm diameter ASTM 4140 steel pin.	Model: 1989, Chevy Silverado 2500 pickup. Mass: 2032kg	**Speed**: 100.6 km/h **Angle**: 25 degrees. **Maximum occupant impact velocity**: 4.2 m/sec **Maximum ridedown acceleration**: 5.4 g's **Roll angle**: 12 degrees	1.346m
Gunnar Prefab AB (15)	NCHRP 350 Test 3-11	Swedish National Road and Transport Research Institute	**Type:** GPLINK pre-cast Temporary Concrete Barrier **Height**: 870-mm (34.25 in) **Length**: 6m. **Base Width**: 440-mm **Top Width**: not known **Installation Length**: not known	Adjacent segments were connected with 680-mm (26.8-in) long, 22-mm (0,87-in) diameter steel rods inserted through holes in steel plates, two of which are cast into each barrier segment. Steel reinforcing consists primarily of ten 16-mm (0.63-in) steel bars.	Pick-up truck	**Maximum occupant impact velocity**: 6.9m/sec **Maximum ridedown acceleration**: 15.4 g's **Roll angle**: 36.2 degrees.	1.76 m

The FHWA criteria for full-scale tests of traffic barriers call for two tests with an 1808 lb (820 kg) passenger car: a low-speed test and a high-speed test (NCHRP Report C440, 1995). Since these tests are extensive and costly, crash simulation is the appropriate choice. Typical analysis for vehicle-barrier crash test involves dynamic nonlinear finite element simulation using a variety of codes such as LS-DYNA (Logan and Tokarz, 1993), which was developed by the Livermore Software Technology Corporation, and is now integrated into the ANSYS finite element software package with extended pre- and post-processing capabilities. It is essential to calibrate the numerical simulations for accurate prediction of the deflection of the traffic barriers. Figure 6 shows a typical pattern of the crash test for a concrete barrier with the trajectory of the truck after impact. This study was recently carried out at the George Washington University (Yonten, et al., 2002). A total termination time of 1½ second was allowed, and the maximum deflection of the barrier was reached in ½ second. Also, at this time the trajectory of the truck becomes predictable, that is, whether the truck will roll over or get deflected.

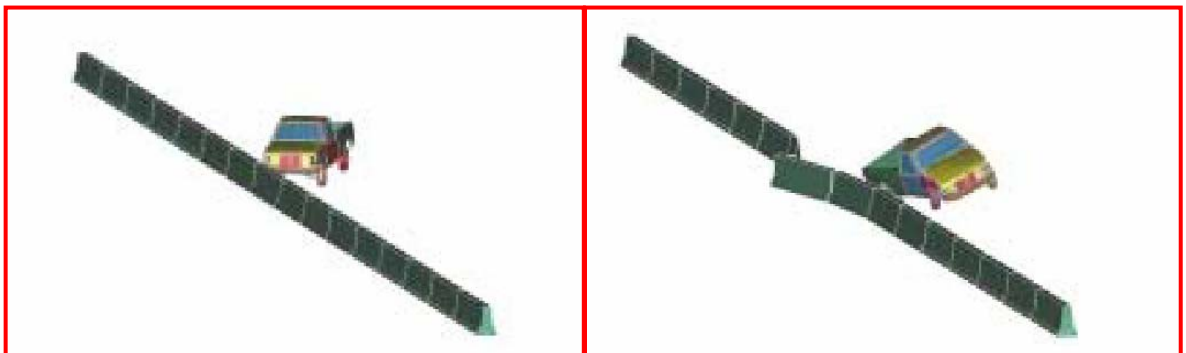


Figure 6 Typical Barrier-Vehicle Crash Test Setup and Simulation (GWU Study[3])

Figure 7 shows the typical crash test and the corresponding simulation for a guardrail. This study was carried out at the University of Cincinnati (Tabiei and Wu, 1997). The figure clearly shows how close the numerical simulation can predict the actual crash test.

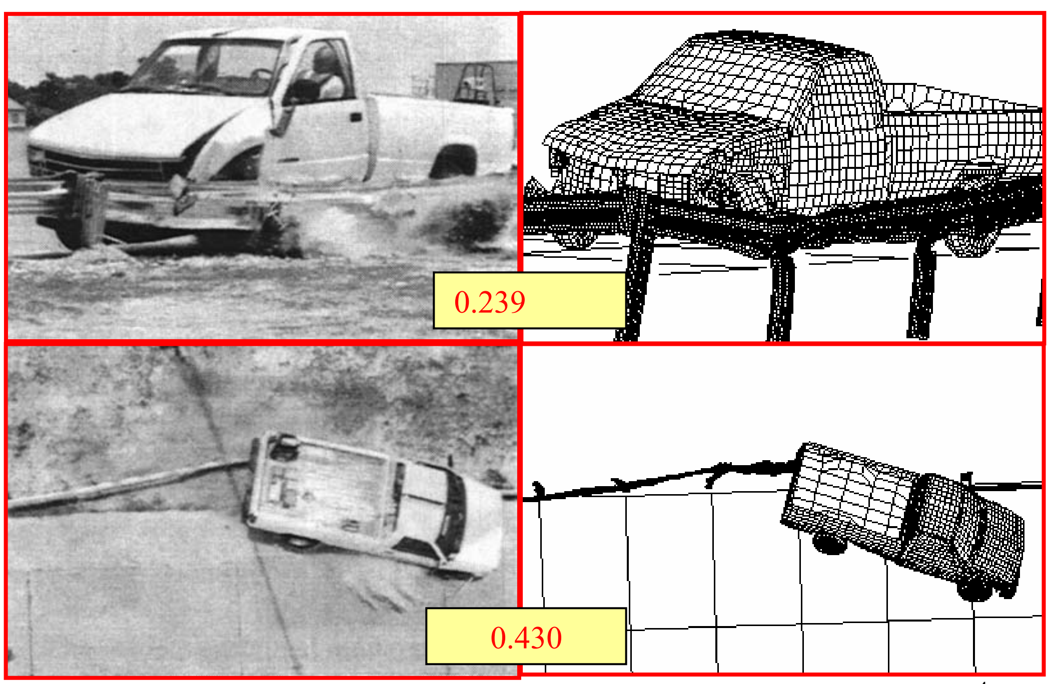


Figure 7. Typical Comparison of Crash Test and Simulation (UC Study[4])

Overall Work Plan

To achieve the objectives of this project, a detailed work plan is proposed, as follows:

Task 1. Literature Review

As clear from the previous section, significant review of literature has already been accomplished by the PIs. Additional review of literature will consist of gathering data on any available studies related to the space behind traffic barriers of the types used by the NCDOT. Furthermore, current guidelines by other states will be reviewed for comparison. Different modeling techniques will be reviewed to ensure accuracy and applicability of the PIs' approach.

Task 2. Numerical Modeling and Calibration

Numerical modeling and calibration of vehicle impact on the NCDOT and the Oregon Type F barriers will be based on the available crash tests of these types of barriers. A typical crash test was shown earlier in Figure 4 for the Oregon Type F barriers. A close examination of the crash elements reveals that the individual PCB segment do not suffer significant deformation. Therefore, the displacements primarily result from the rigid body motion of the PCB assemblage. Hence, if the interest is primarily in evaluating the maximum displacement of PCB under impact as well as the affected segments of the PCB, one can model the impact problem as a rigid body or as a combination of a rigid block and spring-dashpot system. With these idealizations, the collision between the vehicle and the barrier will be formulated using the physics of impulse and momentum, the so-called principle of conservation of momentum, along with a definition of the coefficient of restitution. This task can be carried out using the MSC/Working Model program (1999).

Earlier this year, Araujo, Mirmiran, and Rahman (2003) simulated these crash tests using the MSC/Working Model. Figure 8 shows one such simulation with the safe back distance shown as a solid line parallel to the initial line of the barriers. Both the vehicle and the barriers were modeled accurately in the program both in terms of geometry and weight. In addition, the model required three coefficients; one to account for friction between the barrier and the pavement, one to account for the stiffness of the joints between the different segments of the barrier, and finally, one to account for the energy absorbed by the vehicle during the impact. The latter, which is called coefficient of restitution, is of great importance, since its magnitude can affect the extent of deflection of the barriers.

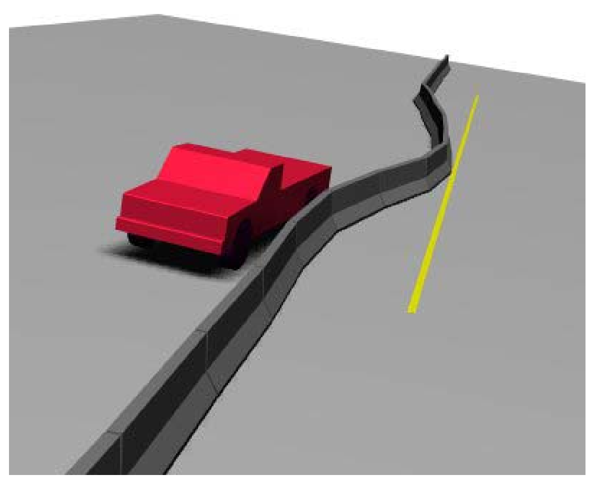


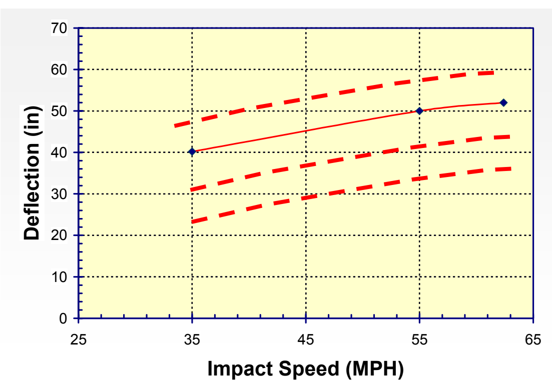
Figure 8. Simulation of Barrier Impact at 35^{o} Angle Using MSC Working Model (Araujo, Mirmiran, and Rahman 2003)

Under this task, it is proposed that a computer program be developed for modeling and simulation of the impact problem within the environment of a commercially available package of MSC/Working Model (MSC, 1999). With this modeling tool, the Research Team will study the vehicle-barrier collision problem in all its details and variations. The model will be calibrated using some of the relevant crash test data available in the literature. Once calibrated, the model will be used to carry out a detailed parametric study regarding the dependence of the maximum displacement on various variables governing the problem. The parameters may include angle of impact, type of barrier, type of connection of the barriers with each other and with the pavement, speed of impact, and other such parameters.

As stated above, the MSC/Working Model is based primarily on rigid body movements, and therefore, is quite sensitive to the selection of the coefficients of friction, stiffness, and restitution. Therefore, it is proposed that in tandem with the MSC modeling approach, a focused and concise finite element model of the vehicle-barrier crash test be developed and calibrated against the crash test results, so that the three necessary coefficients for the MSC model can be derived with high level of confidence for different types of surface conditions, impact angles and truck configurations. This component of the analytical simulation is to serve as a tool to develop a reliable MSC model.

Task 3. Develop Design Charts

Under this task, appropriate design charts will be developed for safe back distance and length of need for the NCDOT barriers as well as Oregon Type F barriers, so that they could be included in the NCDOT traffic control design manual. Figure 9 shows two typical design charts from the earlier work of the PIs (Araujo, Mirmiran, and Rahman 2003). The actual curves are shown for a specific vehicle weight or speed. Additional curves are sketched in as dashed lines to show that an array of curves can be developed for easy reference by traffic design engineers.



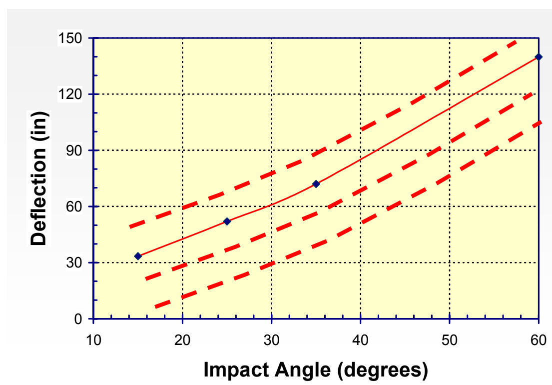


Figure 9. Typical Design Charts for Impact Speed and Impact Angle Using MSC Working Model (Araujo, Mirmiran, and Rahman 2003)

Task 4. Dissemination of Information

Dissemination of information is an integral component of this project, as the results will be provided to the NCDOT in a format appropriate for inclusion on the traffic control design manual. Additionally, quarterly progress reports and a comprehensive final report will be provided to NCDOT.

ANTICIPATED RESULTS AND SIGNIFICANCE

The results of this research will be incorporated as part of the new traffic control design manual for use on all roadway construction projects in North Carolina. Benefits to the NCDOT may be realized as safety, cost-savings, and design efficiency on all roadway construction projects. The deliverable of the project is design aids for the NCDOT barriers and the Oregon Type F barriers for use in the NCDOT traffic control design manual. Both the safe back distance and the length of need will be addressed for tangent and curved segments of highways under construction, with different number of lane configurations. The design guideline provides an easy reference tool for the NCDOT traffic engineers.

The PIs believe this project can directly and immediately provide benefits in terms of safety, efficiency, and cost-savings to the NCDOT, both in short-term and long-term, as described below:

1. Enhance safety of the vehicle occupants and the work crew in construction zones by providing an acceptable distance behind the barrier;
2. Increase operational efficiency by providing adequate safe work area for the crew; and
3. Increase cost-effectiveness of the traffic control procedures and systems by allowing an optimum level of safe distance behind the barrier.

RECOMMENDATIONS FOR IMPLEMENTATION AND TECHNOLOGY TRANSFER

In this section, the main issues regarding implementation and technology transfer of the proposed research will be discussed, as follows:

What is the primary "Product"?

The primary "Product" of this research is clear guidelines on the safe back distance behind the portable concrete barriers, when they are free standing.

What are the secondary products?

The project will also help validate the NCDOT guidelines and recommendations for the back distances in accordance with the FHWA requirements as set by the NCHRP 350.

Who within NCDOT will use the product[s]? (Customers)

This research idea originated from the NCDOT Traffic Engineering And Safety Systems Branch. The customers of the above-described products are the traffic control engineers at various divisions of the NCDOT.

Why should they use the product[s]? (Market)

The traffic engineers at the NCDOT need to know the safe back distance behind free standing PCBs to determine the extent of right of way required on each project, as well as the feasibility of the construction staging operations.

How will they use such product[s]?

The information developed from this research will enable the NCDOT traffic engineers to specify the required right of way and operating widths on their highway construction projects.

What is needed for NCDOT customers to use the product[s]?

Upon completion of the research, seminars would be developed for the NCDOT traffic engineers to present outcomes of the study. Close collaboration between the PIs and the NCDOT personnel will help identify the most appropriate means for technology transfer.

RESOURCES TO BE SUPPLIED BY NCDOT

Based on discussions with Mr. Bourne and Mr. Ishak, they will provide necessary information on the type of charts and design aids that will be useful to the NCDOT.

EQUIPMENT AND FACILITIES

The Department of Civil, Construction, and Environmental Engineering and the Constructed Facilities Laboratory (CFL) at the NCSU have the appropriate computing facilities and software to carry out the work outlined in this project.

TIME REQUIREMENTS

The extent of the proposed program, as described in the previous sections requires 12-15 months of rigorous analysis to achieve the objectives of the project. Progress reports will be submitted every 3 months, and progress meetings will be held every 6 months with the NCDOT Technical Advisory Committee.

QUALIFICATIONS AND ACCOMPLISHMENTS OF RESEARCHERS

The research team consists of Drs. Mirmiran and Rahman. Dr. Mirmiran is a structural engineering professor at the NC State University, and director of technical services at the CFL. He is also a licensed professional engineer and an NSF-Career awardee with several years of experience in industry as well as experimental and analytical research in reinforced and prestressed concrete. He has served on the editorial boards of the ASCE *Journal of Structural Engineering* and *Journal of Composites for Construction*. Dr. Mirmiran has expertise in finite element simulation of impact, and has published on the impact of high velocity objects, such as in turbine missiles, with concrete barriers. Dr. Rahman is an associate professor of geotechnical engineering at the NC State University. His research interests are in the areas of geomechanics, soil dynamics, numerical methods, probabilistic analysis, containment transport in groundwater. Most recently, he completed a brief study on the PCBs under vehicular impacts for the NCDOT.

OTHER COMMITMENTS OF RESEARCHERS

Next year, Dr. Mirmiran will be working on the last year of an NCDOT project on FRP repair, as well as the NCHRP 12-64. However, he will ample time to devote to this important project. Dr. Rahman will also be available for this project.

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